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BIOMEDICAL ENGINEERING | RESEARCH ARTICLE

PLA/PHBV electrospun membrane: Fabrication, coating with conductive PEDOT:PSS and antibacterial activity of drug loaded membrane

Hui Chung Chang¹ and Naznin Sultana^{1,2*}

Abstract: In this study, biodegradable and biocompatible polylactic acid (PLA) and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) blend polymer solutions were electrospun using electrospinning technique. Polymer blend ratio and electrospinning voltage were varied and optimized. The fabricated electrospun PLA/PHBV membranes were dipped into poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) solution to produce conductive PEDOT:PSS coated membranes. The coated and uncoated membranes were investigated using scanning electron microscopy (SEM), field emission scanning electron microscopy (FESEM), energy dispersive X-ray (EDX) and water uptake measurement. PEDOT:PSS coated membranes were then loaded with drug (tetracycline hydrochloride) and their antibacterial activity was investigated. Beadless PLA/PHBV membranes were successfully fabricated. The fabricated PLA/PHBV membranes were rendered conductive by dipping them into poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) solution. Drug loaded membranes showed antibacterial properties which was confirmed by zone inhibition method.

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Dr Naznin Sultana was awarded PhD in 2010 at The University of Hong Kong. She is currently serving as an academic staff in Universiti Teknologi Malaysia. She was registered as a Chartered Scientist (CSci) in 2012 by Science Council, UK and as a Chartered Engineer (CEng) in 2014 from Engineering Council, UK. She has interests in both fundamental science and applied research and she has received a number of research grants from Ministry of Higher Education, Malaysia. Her research interests include biomaterials, tissue engineering, fabrication of scaffolds for tissue engineering, cell-biomaterials interactions and surface modification. She has given many international conference presentations for her research work in The Netherlands, Belgium, Hong Kong etc. She has authored a number of technical papers for her research and author of three books.

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PUBLIC INTEREST STATEMENT

Electrospun membrane has the potential to be used as a scaffold because it mimics extracellular matrix of tissue in terms of scale and morphology. Stimulus-receptive biomaterials based scaffolds or membrane fabricating from established protocols with suitable properties is much highly desired in tissue regeneration. The conductive nature of conductive polymers allows the stimulation of cells cultured upon them through the application of electrical signal. On the other hand, blending of natural polymer with synthetic polymer allows the modulation of properties of both polymers to produce scaffolds or membranes for tissue engineering application. In the current study, electrospinning technique was used to fabricate composite membranes and scaffolds by blending of a synthetic polymer, polylactic acid (PLA) and a natural polymer, poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV). Conductive membranes were prepared by dipping PLA/PHBV electrospun membranes into poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) solution, which is a biocompatible polymer with low inflammatory response.

Subjects: Biomaterials; Drug Targeting; Materials Science

Keywords: electrospinning; scaffold; polylactide; poly(3-hydroxybutyrate-co-3-hydroxyvalerate); PEDOT:PSS

1. Introduction

In the field of tissue engineering, porous scaffolds or membranes are used to provide suitable environment for the regeneration of cells or tissues (O'Brien, 2011; Sultana, 2014). There are several techniques used to fabricate biodegradable scaffolds, which include self-assembly, phase separation (Liu & Ma, 2009), freeze drying (Jin, Sultana, Baba, Hamdan, & Ismail, 2015; Sadeghpour, Amirjani, Hafezi, & Zamanian, 2014) and electrospinning (Hassan, Sultana, & Hamdan, 2014; Hassan, Sun, & Sultana, 2014). Electrospinning is a technique which utilizes electrostatic force to fabricate micro or nanofibers. There are several advantages of electrospinning as compared to other methods like self-assembly and phase separation. Among the advantages of electrospinning are its simplicity; and the fact that a wide range of polymers and ceramics can be used (Rasal & Hirt, 2009).

Biodegradable polymers, such as polylactic acid (PLA), poly(glycolic acid) (PGA) and their copolymer (PLGA) are commonly used materials to fabricate scaffolds. PLA, a synthetic biodegradable thermoplastic polyester has been researched extensively and showed great potential in biomedical applications (Feng, Shen, Fu, & Shao, 2011). On the other hand, poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) is a natural biodegradable polymer with complete biocompatibility and has been researched for biomedical applications such as sutures, medical implants, and tissue engineering scaffolds (Feng et al., 2011). Our previous work demonstrated that blending of PLA with PHBV enhances the scaffold wettability when compared to pure electrospun PLA (Chang et al., 2016).

Conductive polymers such as polyaniline (PANI), polypyrrole (PPy) and polythiophene (PTh) have recently been investigated by researchers in the field of microelectronics, biomedical and tissue engineering applications (Aznar-Cervantes et al., 2012; Owens & Malliaras, 2010; Xu et al., 2014). Researchers have been showing increasing interest in PEDOT for biomedical applications owing to its good oxidative stability (Groenendaal, Jonas, Freitag, Pielartzik, & Reynolds, 2000). PEDOT can be doped with poly(4-styrenesulfonate) (PSS), producing a water soluble copolymer with good stability and good film-forming properties (Reddy, Jeong, Lee, & Raghu, 2010). The thermal, electrochemical and oxidative stability properties of PEDOT:PSS allow it to be used in various applications such as flexible electrodes, electrochromical displays, transistors, and nanocomposites (Abrigo, McArthur, & Kingshott, 2014; Chen, Nilsson, Kugler, Berggren, & Remonen, 2002; Daoud, Xin, & Szeto, 2005; Heuer, Wehrmann, & Kirchmeyer, 2002; Qi et al., 2013).

Electrospun membranes with antibacterial properties can be used as wound dressing material for skin infections and chronic wounds (Hong et al., 2008). A wide variety of low molecular weight drugs can be incorporated into electrospun scaffolds, for example, tetracycline hydrochloride (TCH) (Chong, Hassan, & Sultana, 2015), mefoxin, paxlitaxel, and rifampin. Previous research showed that polyurethane/poly(lactide-co-glycolide) (PEUU/PLGA) fibrous sheets incorporated with TCH prevented wound dehiscence and abscess formation in a contaminated rat abdominal model (Sultana & Abdul Kadir, 2011). However, there is still no study reported regarding incorporation of TCH into PEDOT:PSS coated electrospun membranes.

This study aims to fabricate beadless PLA/PHBV electrospun membranes using electrospinning technique with conductive properties for tissue engineering application. The conductive nature of conductive polymers allows the stimulation of cells cultured upon them through the application of electrical signal. The morphology of the electrospun membranes were characterized by SEM and FESEM. By dipping these membranes into PEDOT:PSS solution, conductive PEDOT:PSS coated membranes were produced. Water uptake properties were tested using water uptake measurement technique. The membranes were also loaded with tetracycline hydrochloride and their antibacterial properties were investigated against Gram-positive and Gram-negative bacteria.

2. Materials and methods

2.1. Materials

PLA (molecular weight, $M_w = 2,20,000 \text{ g mol}^{-1}$, product name Biomer L9000) was obtained from Biomer, Kraling, Germany. PHBV ($M_w = 6,80,000 \text{ g mol}^{-1}$) with PHV content of 12 mol% was purchased from Sigma Aldrich. Chloroform (Fisher Scientific) was used as the solvent. PEDOT:PSS in the form of water suspension (1.1 wt%) was also bought from Sigma Aldrich. Tetracycline hydrochloride was obtained from Calbiochem. All other chemicals and reagents were of analytical grade.

2.2. Methods

2.2.1. Preparation of PLA/PHBV-based polymer solutions

Different blend ratios (60:40 and 50:50) of 20% (w/v) PLA/PHBV solution were prepared by dissolving PLA and PHBV pellets in chloroform. In order to produce 20% (w/v) 60:40 PLA/PHBV polymer solution, 1.2 g PLA and 0.8 g PHBV were dissolved in 10 ml of chloroform. Similarly, 20% (w/v) 50:50 PLA/PHBV polymer solution was prepared by dissolving 1 g PLA and 1 g PHBV in 10 ml of chloroform. All the solutions prepared were magnetically stirred using magnetic stirrer (C-MAG-HS7, IKA®) for 4 h at 50°C inside a fume hood (Esco, Ascent® Max).

2.2.2. Fabrication of PLA/PHBV electrospun membranes

An electrospinning unit was used to fabricate PLA/PHBV electrospun membranes using electrospinning technique. The prepared polymer solutions were loaded into a 10 ml syringe. The syringe was then attached with a 23 gauge stainless steel needle and was placed on a syringe pump (New Era Pump Systems, Inc.). The positive charge electrode of the electrospinning unit was connected to the nozzle. Meanwhile, the grounding electrode was attached to the collector, in which the aluminium foil (6 cm × 8 cm) was placed for the deposition of electrospun fibers. In this experiment, the manipulated parameters including polymer blend ratio and concentration, flow rate, and applied voltage were optimized to achieve continuous spinning and smooth fibres. The distance between the nozzle and collector was set constant at 15 cm. The electrospinning process was carried out at temperatures in the range of 18–22°C.

2.2.3. Coating of PEDOT:PSS on electrospun PLA/PHBV membranes

As described in our previous research work, PLA/PHBV membranes were dipped into solution of PEDOT:PSS to fabricate PEDOT:PSS coated PLA/PHBV membranes (Chang et al., 2016). 10% (v/v) PEDOT:PSS and 30% (v/v) PEDOT:PSS solution were prepared by mixing PEDOT:PSS [1.1% (w/w) water suspension] with isopropanol in a ratio of 1:9 and 3:7. The electrospun PLA/PHBV membranes were dissected into 16 mm diameter circular discs and dipped into the mixed solution of PEDOT:PSS and isopropanol for 30 min. The coated membranes were then removed from the PEDOT:PSS solutions, and dried inside an oven for 3 h at 40°C.

2.2.4. Characterization of PLA/PHBV membranes and PEDOT:PSS coated membranes

2.2.4.1. Morphology. The electrospun membranes were coated with platinum and their morphology were examined using a Field Emission Scanning Electron Microscope (FESEM, SU8020, Hitachi) and a scanning electron microscope (SEM, TM3000, Hitachi). The diameters of at least 45–50 fibers were measured using ImageJ software and the average diameter was calculated for each sample.

2.2.4.2. Energy dispersive X-ray spectroscopy. An energy dispersive X-ray spectroscopy (FESEM, SU8020, Hitachi) was used to confirm the presence of elements in the PEDOT:PSS coated membranes. The weight percentage of sulfur element in 30% PEDOT:PSS coated PLA/PHBV membrane and 10% PEDOT:PSS coated PLA/PHBV membrane was compared.

2.2.4.3. Water uptake measurement. As-fabricated PLA, PHBV, PLA/PHBV-based electrospun membranes and the coated PLA/PHBV membranes were cut into samples with dimension of $3 \times 4 \text{ cm}^2$. These samples were then weighted and immersed in deionized water for 2, 5, 10, 15, 20, 25, 30, 45 and 60 min (Sultana & Abdul Kadir, 2011). Next, the samples were taken out periodically, blotted dry with tissue paper to eliminate excess water at the surface, and weighted. The percentages of water uptake were calculated using the following equation (Sultana & Abdul Kadir, 2011):

$$\text{Water uptake (\%)} = \frac{W_w - W_d}{W_d} \times 100 \quad (\text{i})$$

where W_w is the wet sample weight after immersion in deionized water, and W_d is the dry sample weight before immersion.

2.2.5. Incorporation of drug and Antibacterial Evaluation

Tetracycline hydrochloride (TCH) was used as the model drug in this study. 0.2 g of TCH powder was pre-dissolved in 10 ml of methanol to produce 2% w/v TCH solution. PLA/PHBV and PEDOT:PSS coated PLA/PHBV membranes were cut into 16 mm-diameter circular discs. Each circular disc membrane was immersed in 1 ml of TCH solution overnight for the drug to be successfully loaded into the membranes.

Antibacterial activity of PLA/PHBV and PEDOT:PSS coated PLA/PHBV electrospun membranes with and without TCH coating were investigated using zone inhibition method to compare the antibacterial activity between drug loaded samples and samples without loaded drugs. *Escherichia coli* (Gram-negative bacteria) and *Staphylococcus aureus* (Gram-positive bacteria) were selected as model microorganisms. Using the spread plate method, the nutrient agar plates were inoculated with 1 ml of bacterial suspension containing 10^8 cfu/ml for each type of bacteria. The circular discs membranes were then carefully placed on the inoculated plates and incubated for 24 h at 37°C . Zones of inhibition were determined by measuring the diameter of the clear area formed around each scaffold.

2.2.6. Statistical Analysis

At least three samples were tested and the average and standard deviation were calculated and analysed.

3. Results and discussion

3.1. Morphology of PLA/PHBV-based electrospun membranes

Figure 1 shows the FESEM micrographs of 20% (w/v) PLA/PHBV electrospun membranes at different blend ratio and applied voltage. As shown in Table 1 and Figure 1, PLA/PHBV membrane with weight ratio of 50:50 had relatively narrow range of fiber diameter (198–4,632 nm) when compared to PLA/PHBV membrane with weight ratio 60:40 (187–8,714 nm and 142–10,696 nm). The fibers of PLA/PHBV membrane with weight ratio of 50:50 were more uniform. Two different ranges of fibers were formed as shown in Table 1 and Figure 1. However, although a bimodal distribution was observed, most of the fibers were in range II and fall into the lower range (sub-micron or nm) category. There was not much difference in the average fiber diameter in the lower range (range II) for the PLA/PHBV membrane with weight ratio of 50:50 and 60:40. For the higher range (range I, micron size), the average fiber diameter of PLA/PHBV membrane with weight ratio of 60:40 was much higher than the membrane with weight ratio of 50:50. It was reported that polymers experience phase separation at high humidity, which causes thermodynamic instability, contributes to the wider range of fiber diameter distribution or bimodal distribution (Chang et al., 2016; Huang, Bui, Manickam, & McCutcheon, 2011). Beadless membranes with smaller average fiber diameter and uniform fiber diameter ranges are suitable for cell proliferation and attachment due to higher total surface area

Figure 1. FESEM micrographs and distribution of fiber diameters for 20% (w/v) (a) 60/40 PLA/PHBV at 16.5 kV; 60/40 PLA/PHBV at 18 kV (b); 50/50 PLA/PHBV at 25 kV (c).

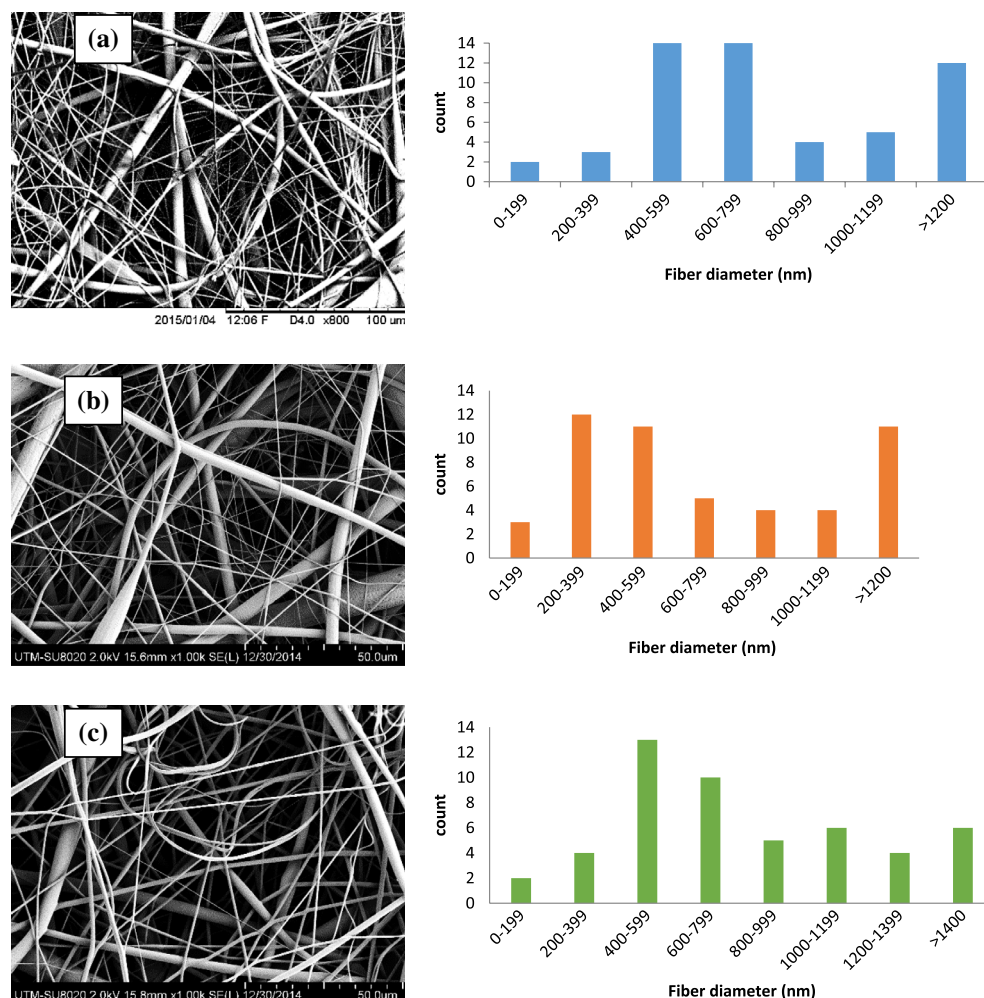
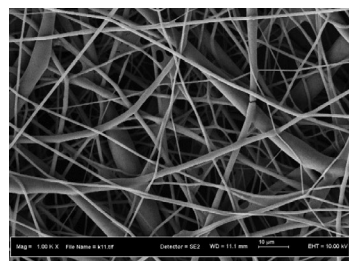
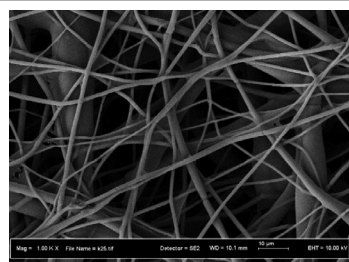


Table 1. Electrospinning parameters for 20% (w/v) PLA/PHBV of different weight ratio

Weight ratio (PLA/PHBV)	Applied voltage (kV)	Range of fibers' diameter (nm)	Average fibers diameter (nm)	
			Range I (Micron size)	Range II (Sub-micron size)
60:40	16.5	187-8,714	4,220 ± 1.90	540 ± 0.14
60:40	18	142-10,696	4,610 ± 2.87	390 ± 0.20
50:50	25	198-4,632	2,720 ± 0.96	540 ± 0.21

to volume ratio (Dhandayuthapani, Yoshida, Maekawa, & Kumar, 2011). Meanwhile, FESEM micrographs of PEDOT:PSS coated membranes were shown in Table 2. It was observed from Table 2 that 30 or 10% coating with PEDOT:PSS did not alter the morphology of as fabricated electrospun membrane. The surface of the membranes was simply adsorbed with PEDOT:PSS coating and the pores were not blocked with the coating.

Table 2. Weight percentage of S on PEDOT:PSS coated membranes and their FESEM micrographs

Sample	Weight % of S	FESEM micrographs
30% PEDOT:PSS coated PLA/PHBV	13.0	
10% PEDOT:PSS coated PLA/PHBV	5.8	

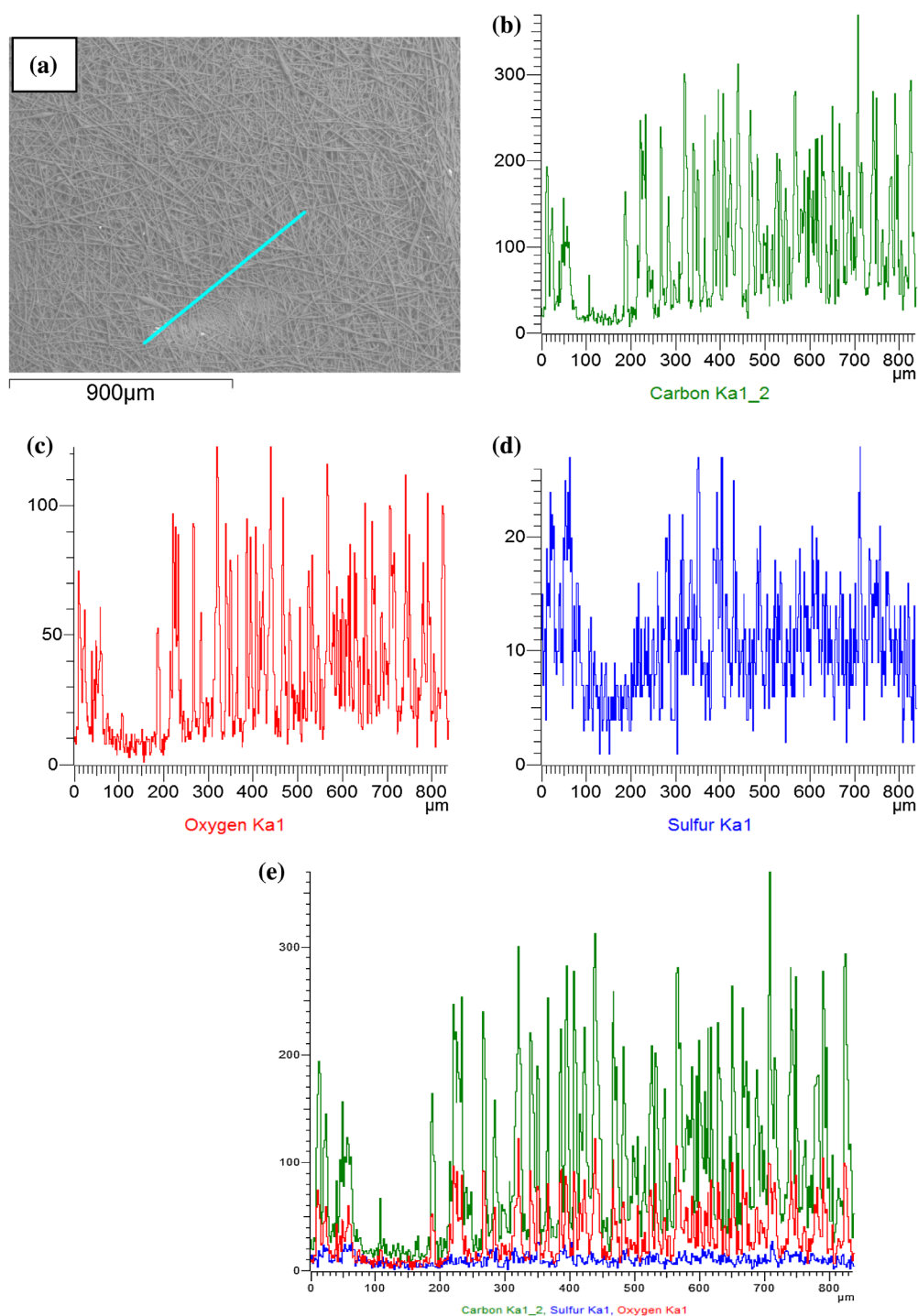
3.2. Energy dispersive X-ray (EDX) analysis

In order to confirm the presence of Sulfur (S) on the membranes, 10% (v/v) and 30% (v/v) PEDOT:PSS coated PLA/PHBV membranes were observed using energy dispersive X-ray spectroscopy (EDX). S is an element found in PEDOT:PSS but not in PLA and PHBV. EDX analyses showed that higher weight ratio of S was present in 30% (v/v) PEDOT:PSS coated membranes compared to 10% (v/v) PEDOT:PSS coated membranes (Table 2). EDX line scan analysis was performed on the membranes to observe the distribution of elements along a drawn line. The results of line scan analysis for 30% and 10% PEDOT:PSS coated PLA/PHBV membranes are shown in Figures 2 and 3. These results proved that the PEDOT:PSS was successfully coated onto the membranes as the elemental line scan confirmed the presence of S. It is expected that coating with PEDOT:PSS will render the membranes more conducive for cell attachment to be used in tissue engineering.

3.3. Water uptake

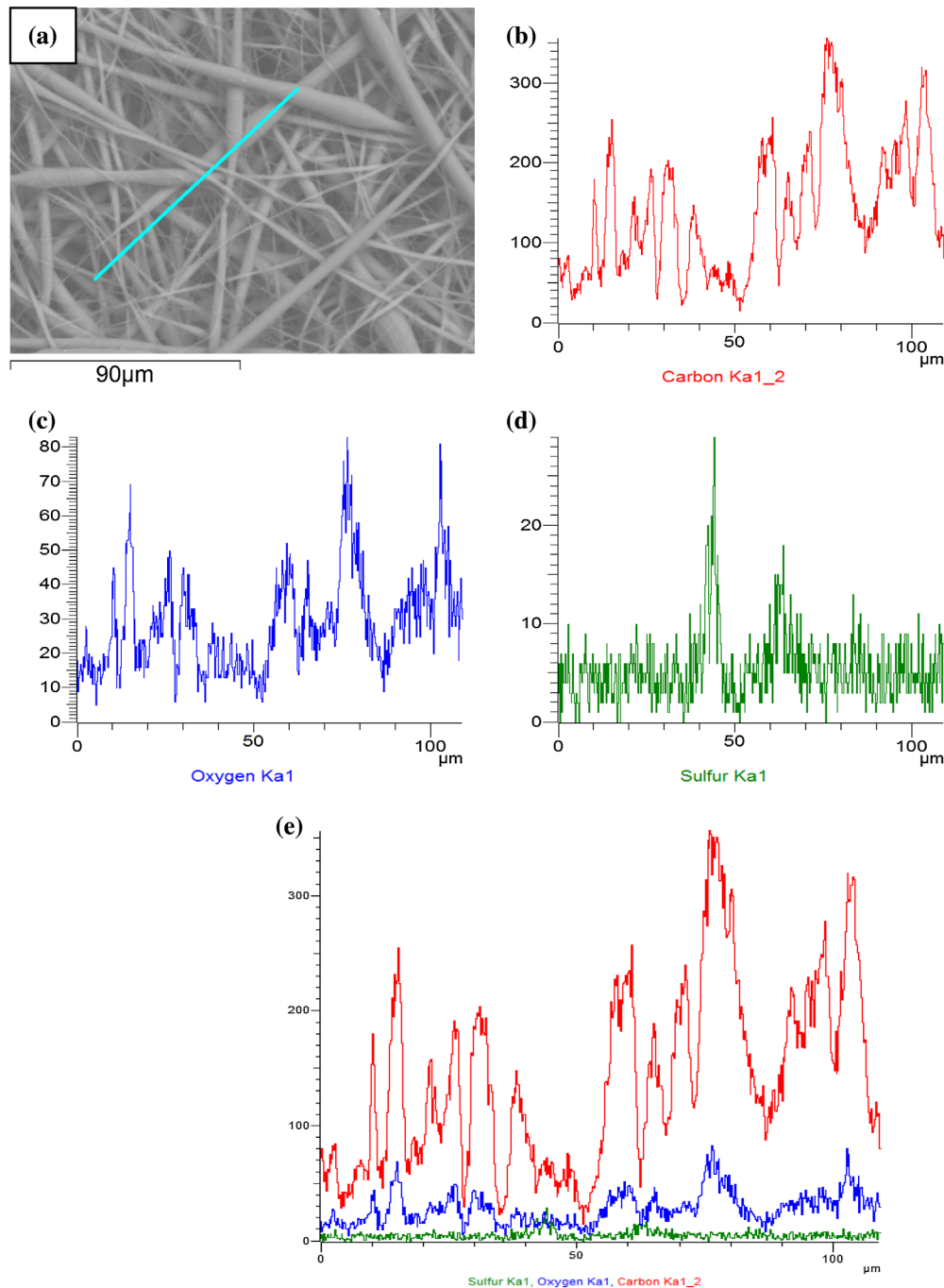
Water uptake percentage of PLA, PHBV, PLA/PHBV and the PEDOT:PSS coated membranes were studied at different time intervals (Figure 4). The coated membranes showed excellent water uptake properties compared to their non-coated counterpart (PLA/PHBV). At 60 min, the average water uptake showed a great increase from 153% for PLA/PHBV membrane to 214% for 30% (v/v) PEDOT:PSS coated PLA/PHBV membrane. On the other hand, the water uptake for pure PLA and pure PHBV had much lower water uptake property than the other membranes. These results indicated that the incorporation of hydrophilic materials, such as PEDOT:PSS, enhanced the hydrophilic properties of the coated membrane, which can help in facilitating cell adhesion as well as cell proliferation (Kim, Khil, Kim, Lee, & Jahng, 2006).

Figure 2. EDX line scans profile of 30% (v/v) PEDOT:PSS coated PLA/PHBV membrane for different elements across the (a) drawn line in SEM micrograph; (b) Carbon, (c) Oxygen, (d) Sulfur and (e) Line scanning elemental profiles of C, O, and S elements.



The water uptake percentage outcomes of PEDOT:PSS coated membranes were also better than commercially wound dressing material (Comfeel). Comfeel, which is designed for high water absorption from the wounds surface, had a water uptake percentage of around 120% after being immersed in water for 24 h (Zahedi et al., 2012). The increase in water uptake of the PEDOT:PSS coated membranes was due to the presence of functional group of -OH along the PSS chain. Three to four water molecules can be absorbed by each PSS chain (Zhou et al., 2014).

Figure 3. EDX line scans profile of 10% (v/v) PEDOT:PSS coated PLA/PHBV membrane for different elements across the (a) drawn line in SEM micrograph; (b) Carbon, (c) Oxygen, (d) Sulfur and (e) Line scanning elemental profiles of C, O, and S elements.



3.4. Antibacterial evaluation of drug loaded membranes

The antibacterial activity of PLA/PHBV and PEDOT:PSS coated PLA/PHBV electrospun membranes as well as the TCH-coated samples were tested against two types of bacteria, namely *S. aureus* (Gram-positive bacteria) and *E. coli* (Gram-negative bacteria) for 24 h. The antigrowth regions of bacteria in different samples, also known as inhibition zones, were evaluated and the results were presented in Table 3. After 24 h, increased inhibition zone of average diameter of 4.0 ± 0.10 cm was clearly viewed for the drug-loaded samples. For the sample which was not coated with PEDOT:PSS and was not loaded with drugs, no inhibition zone was observed. PEDOT:PSS coated PLA/PHBV membrane had a lower value of inhibition zone. These results indicated that PLA/PHBV electrospun membrane do not

Figure 4. Percentage of water uptake of PLA, PHBV, PLA/PHBV and PEDOT:PSS coated PLA/PHBV membranes.

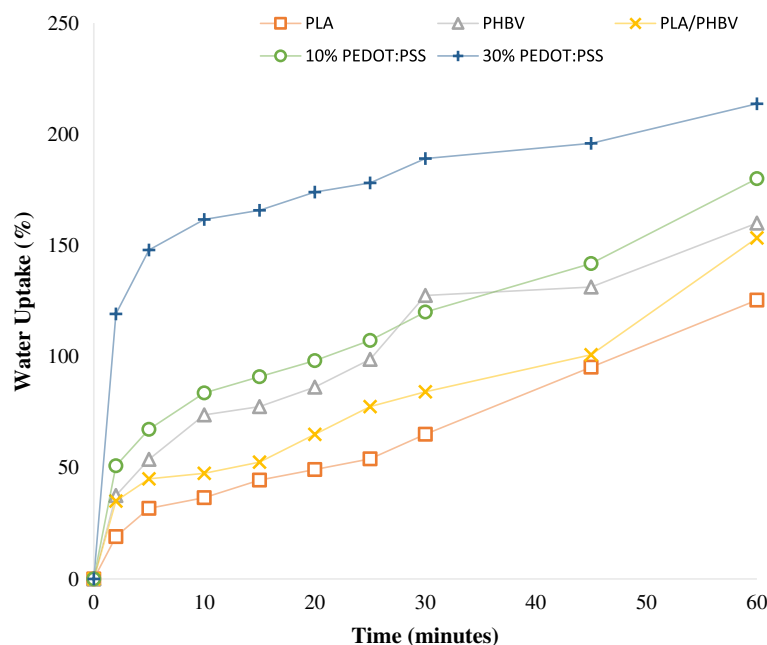
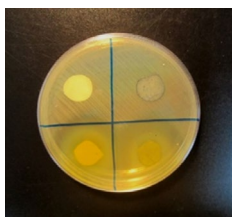
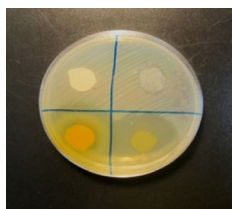


Table 3. Antibacterial activity of PLA/PHBV and PEDOT:PSS coated PLA/PHBV membranes with and without Tetracycline Hydrochloride coating against *S. aureus* and *E. coli* after incubated for 24 h

Samples	Increment of inhibition zone average diameter (cm)	
	<i>S. aureus</i>	<i>E. coli</i>
		
PLA/PHBV (top left)	0	0
PEDOT:PSS coated PLA/PHBV (top right)	0.2 ± 0.01	0.2 ± 0.01
PLA/PHBV with TCH (bottom left)	4.0 ± 0.10	4.0 ± 0.15
PEDOT:PSS coated PLA/PHBV with TCH (bottom right)	4.0 ± 0.10	4.0 ± 0.15

possess antibacterial property. However, when loaded with TCH, drug-loaded electrospun membranes showed better antibacterial property and had the prospect to be used for protection against surgery infection (Haroosh, Dong, & Lau, 2014). Previous research had showed polyurethane/poly(lactide-co-glycolide) (PEUU/PLGA) fibrous sheets loaded with antibiotic tetracycline hydrochloride prevented wound infection and abscess formation in a contaminated rat abdominal model (Hong et al., 2008).

4. Conclusions

Using electrospinning technique, beadless PLA/PHBV membranes were successfully fabricated with flow rate of 1 ml/h, 25 kV applied voltage, and blend ratio of 50:50. The electrospun membranes were rendered conductive by coating the membranes with conductive PEDOT:PSS solution. EDX analyses showed that the coating of PEDOT:PSS was successful. The fabricated conductive membranes showed higher water uptake properties, making them potential candidates to be used for tissue engineering application. Antibacterial evaluation using zone inhibition method confirmed the antibacterial properties of the TCH coated membranes against *S. aureus* and *E. coli*. Hence, PEDOT:PSS coated PLA/PHBV membrane with TCH coating are potential candidate to be used to inhibit bacterial infections in tissue regeneration application.

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References

- Abrigo, M., McArthur, S. L., & Kingshott, P. (2014). Electrospun nanofibers as dressings for chronic wound care: Advances, challenges, and future prospects. *Macromolecular Bioscience*, 14, 772–792. <https://doi.org/10.1002/mabi.201300561>
- Aznar-Cervantes, S., Roca, M. I., Martinez, J. G., Meseguer-Olmo, L., Cenis, J. L., Moraleda, J. M., & Otero, T. F. (2012). Fabrication of conductive electrospun silk fibroin scaffolds by coating with polypyrrole for biomedical applications. *Bioelectrochemistry*, 85, 36–43. <https://doi.org/10.1016/j.bioelechem.2011.11.008>
- Chang, H. C., Sun, T., Sultana, N., Lim, M. M., Khan, T. H., & Ismail, A. F. (2016). Conductive PEDOT:PSS coated polylactide (PLA) and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) electrospun membranes: Fabrication and characterization. *Materials Science and Engineering: C*, 61, 396–410. <https://doi.org/10.1016/j.msec.2015.12.074>
- Chen, M., Nilsson, D., Kugler, T., Berggren, M., & Remonen, T. (2002). Electric current rectification by an all-organic electrochemical device. *Applied Physics Letters*, 81, 2011–2013. <https://doi.org/10.1063/1.1506785>
- Chong, L. H., Hassan, M. I., & Sultana, N. (2015). Electrospun polycaprolactone (PCL) and PCL/nano-hydroxyapatite (PCL/nHA)-based nanofibers for bone tissue engineering application. In *10th Asian Control Conference (ASCC)* (pp. 1–4). Kota Kinabalu: IEEE.
- Daoud, W. A., Xin, J. H., & Szeto, Y. S. (2005). Polyethylenedioxythiophene coatings for humidity, temperature and strain sensing polyamide fibers. *Sensors and Actuators B: Chemical*, 109, 329–333. <https://doi.org/10.1016/j.snb.2004.12.067>
- Dhandayuthapani, B., Yoshida, Y., Maekawa, T., & Kumar, D. S. (2011). Polymeric scaffolds in tissue engineering application: A review. *International Journal of Polymer Science*, 2011, 19.
- Feng, S., Shen, X., Fu, Z., & Shao, M. (2011). Preparation and characterization of gelatin-poly(L-lactic acid)/poly(hydroxybutyrate-co-hydroxyvalerate) composite nanofibrous scaffolds. *Journal of Macromolecular Science, Part B*, 50, 1705–1713. <https://doi.org/10.1080/00222348.2010.541002>
- Groenendaal, L., Jonas, F., Freitag, D., Pielartzik, H., & Reynolds, J. R. (2000). Poly(3,4-ethylenedioxythiophene) and its derivatives: Past, present, and future. *Advanced Materials*, 12, 481–494. [https://doi.org/10.1002/\(ISSN\)1521-4095](https://doi.org/10.1002/(ISSN)1521-4095)
- Haroosh, H. J., Dong, Y., & Lau, K.-T. (2014). Tetracycline hydrochloride (TCH)-loaded drug carrier based on PLA:PCL nanofibre mats: Experimental characterisation and release kinetics modelling. *Journal of Materials Science*, 49, 6270–6281. <https://doi.org/10.1007/s10853-014-8352-7>
- Hassan, M. I., Sultana, N., & Hamdan, S. (2014). Bioactivity assessment of poly(ϵ -caprolactone)/hydroxyapatite electrospun fibers for bone tissue engineering application. *Journal of Nanomaterials*, 1–6. doi:10.1155/2014/573238
- Hassan, M. I., Sun, T., & Sultana, N. (2014). Fabrication of nanohydroxyapatite/poly(caprolactone) composite microfibers using electrospinning technique for tissue engineering applications. *Journal of Nanomaterials*, 2014, 7.
- Heuer, H. W., Wehrmann, R., & Kirchmeyer, S. (2002). Electrochromic window based on conducting poly(3,4-ethylenedioxythiophene)-poly(styrene sulfonate). *Advanced Functional Materials*, 12, 89–94. [https://doi.org/10.1002/\(ISSN\)1616-3028](https://doi.org/10.1002/(ISSN)1616-3028)
- Hong, Y., Fujimoto, K., Hashizume, R., Guan, J., Stankus, J. J., Tobita, K., & Wagner, W. R. (2008). Generating elastic, biodegradable polyurethane/poly(lactide-co-glycolide) fibrous sheets with controlled antibiotic release via two-stream electrospinning. *Biomacromolecules*, 9, 1200–1207. <https://doi.org/10.1021/bm701201w>
- Huang, L., Bui, N. N., Manickam, S. S., & McCutcheon, J. R. (2011). Controlling electrospun nanofiber morphology and mechanical properties using humidity. *Journal of Polymer Science Part B: Polymer Physics*, 49, 1734–1744. <https://doi.org/10.1002/polb.v49.24>
- Jin, R. M., Sultana, N., Baba, S., Hamdan, S., & Ismail, A. F. (2015). Porous PCL/chitosan and nHA/PCL/chitosan scaffolds for tissue engineering applications: Fabrication and evaluation. *Journal of Nanomaterials*, 16, 138.
- Kim, C. H., Khil, M. S., Kim, H. Y., Lee, H. U., & Jahng, K. Y. (2006). An improved hydrophilicity via electrospinning for enhanced cell attachment and proliferation. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, 78, 283–290. [https://doi.org/10.1002/\(ISSN\)1552-4981](https://doi.org/10.1002/(ISSN)1552-4981)

- Liu, X., & Ma, P. X. (2009). Phase separation, pore structure, and properties of nanofibrous gelatin scaffolds. *Biomaterials*, 30, 4094–4103.
<https://doi.org/10.1016/j.biomaterials.2009.04.024>
- O'Brien, F. J. (2011). Biomaterials & scaffolds for tissue engineering. *Materials Today*, 14, 88–95.
[https://doi.org/10.1016/S1369-7021\(11\)70058-X](https://doi.org/10.1016/S1369-7021(11)70058-X)
- Owens, R. M., & Malliaras, G. G. (2010). Organic electronics at the interface with biology. *MRS Bulletin*, 35, 449–456.
<https://doi.org/10.1557/mrs2010.583>
- Qi, R., Guo, R., Zheng, F., Liu, H., Yu, J., & Shi, X. (2013). Controlled release and antibacterial activity of antibiotic-loaded electrospun halloysite/poly(lactic-co-glycolic acid) composite nanofibers. *Colloids and Surfaces B: Biointerfaces*, 110, 148–155.
<https://doi.org/10.1016/j.colsurfb.2013.04.036>
- Rasal, R. M., & Hirt, D. E. (2009). Toughness decrease of PLA-PHBHx blend films upon surface-confined photopolymerization. *Journal of Biomedical Materials Research Part A*, 88A, 1079–1086.
<https://doi.org/10.1002/jbm.a.v88a.4>
- Reddy, K. R., Jeong, H. M., Lee, Y., & Raghun, A. V. (2010). Synthesis of MWCNTs-core/thiophene polymer-sheath composite nanocables by a cationic surfactant-assisted chemical oxidative polymerization and their structural properties. *Journal of Polymer Science Part A: Polymer Chemistry*, 48, 1477–1484.
<https://doi.org/10.1002/pola.v48.7>
- Sadeghpour, S., Amirjani, A., Hafezi, M., & Zamanian, A. (2014). Fabrication of a novel nanostructured calcium zirconium silicate scaffolds prepared by a freeze-casting method for bone tissue engineering. *Ceramics International*, 40, 16107–16114. <https://doi.org/10.1016/j.ceramint.2014.07.039>
- Sultana, N. (2014). *Biodegradable polymer-based scaffolds for bone tissue engineering*. Berlin: Springer.
- Sultana, N., & Abdul Kadir, M. R. (2011). Study of *in vitro* degradation of biodegradable polymer based thin films and tissue engineering scaffolds. *African Journal of Biotechnology*, 10, 18709–18715.
- Xu, H., Holzwarth, J. M., Yan, Y., Xu, P., Zheng, H., Yin, Y., ... Ma, P. X. (2014). Conductive PPY/PDLLA conduit for peripheral nerve regeneration. *Biomaterials*, 35, 225–235.
<https://doi.org/10.1016/j.biomaterials.2013.10.002>
- Zahedi, P., Karami, Z., Rezaei, I., Jafari, S. H., Mahdavi, P., Abdolghaffari, A. H., & Abdollahi, M. (2012). Preparation and performance evaluation of tetracycline hydrochloride loaded wound dressing mats based on electrospun nanofibrous poly(lactic acid)/poly(ϵ -caprolactone) blends. *Journal of Applied Polymer Science*, 124, 4174–4183.
<https://doi.org/10.1002/app.v124.5>
- Zhou, J., Anjum, D. H., Chen, L., Xu, X., Ventura, I. A., Jiang, L., & Lubineau, G. (2014). The temperature-dependent microstructure of PEDOT/PSS films: Insights from morphological, mechanical and electrical analyses. *Journal of Materials Chemistry C*, 2, 9903–9910.
<https://doi.org/10.1039/C4TC01593B>



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